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OARE STS-75 (USMP-3) Final Report

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1.0 INTRODUCTION

The report is organized into sections representing the phases of work performed in analyzing the STS-75 (USMP-3) results. Section 1 briefly outlines the OARE system features, coordinates, and measurement parameters. Section 2 describes the results from STS-75. The mission description, data calibration, and representative data obtained on STS-75 are presented. Also, the anomalous performance of OARE on STS-75 is discussed. Finally, Section 3 presents a discussion of accuracy achieved and achievable with OARE.

1.1 OARE System Features

The Orbital Acceleration Research Experiment (OARE) contains a tri-axial accelerometer which uses a single free-floating (non-pendulous) electrostatically suspended cylindrical proofmass. The accelerometer sensor assembly is mounted on dual-gimbal platform which is controlled by a microprocessor in order to perform in-flight calibrations. Acceleration measurements are normally processed and stored in the OARE flight computer memory and, simultaneously, the unprocessed data are recorded on the shuttle payload tape. The payload tape recorder data are telemetered periodically to ground stations at several hour intervals during flight via tape recorder playback (data dumps).

OARE's objectives are to measure quasi-steady accelerations, to make high resolution low-frequency acceleration measurements in support of the micro-gravity community, and to measure Orbiter aerodynamic performance on orbit and during reentry. There are several features which make the OARE desirable for making highly accurate, low-frequency acceleration measurements. OARE is the first high resolution, high accuracy accelerometer flight design which has the capability to perform both bias and scale factor calibrations in orbit. Another design feature is the OARE sensor electrostatic suspension which has much less bias temperature sensitivity than pendulous accelerometers. Given the nature of the OARE sensor and its in-flight calibration capability, OARE stands alone in its ability to characterize the low-frequency environment of the Orbiter with better than 10 nano-g resolution and approximately 50 nano-g on-orbit accuracy.

1.2 Coordinate Systems

Two coordinate systems are used in this report -- the OARE axes centered at the OARE sensor proofmass centroid and the Orbiter aircraft body axes centered at the Orbiter's center of gravity. The direction from tail to nose of the orbiter is +X in both systems. The direction from port wing to starboard wing is +Z in the OARE system and +Y in the Orbiter system. The direction from the Orbiter belly to the top of the Orbiter fuselage is +Y in the OARE system and -Z in the Orbiter system. This sensor-to-body coordinate alignment referred to above is the nominal flight alignment and was utilized for OARE data collection during STS-75.

In discussions of OARE calibrations of bias and scale factor, the OARE reference system is used. However, the flight acceleration data are given in the Orbiter body reference system. The sign convention is such that when there is a forward acceleration of the Orbiter (such as the OMS firing), this is then reported as a positive X-axis acceleration. All accelerations given in this report refer to the OARE location.

1.3 Sensor Measurement Parameters

There are three sensor ranges, A, B, and C, for each OARE axis, which are controlled by auto-ranging software logic. The full scale ranges and resolutions (corresponding to one count) are given in Table 1. In any case where the sensor channel is driven into saturation, the output is set to 1.5 times full scale of range A with the sign of the saturation signal included.

Table 1. OARE Sensor Ranges and Resolutions

	Nominal Full Scale Range in micro-Gs	
Range	X-Axis	Y & Z Axes
A	10,000	25,000
B	1,000	1,970
C	100	150
	Resolution in nano-Gs SF_N in nano-Gs/count	
Range	X-Axis	Y & Z Axes
A	305.2	762.9
B	30.52	60.12
C	3.052	4.578

2.0 STS-75 (USMP-3) MISSION RESULTS

This section describes the results from STS-75 as derived from post-flight processing of the payload tape recorder data. Due to a glitch in the software, the on-board stored EEPROM processed acceleration data were not available. Results in this report are from data recorded on the payload tape recorder and processed after the mission. During the mission, preliminary calibrations and accelerations were reported in near-real time by Lewis Research Center with calibration support from Canopus Systems.

2.1 STS-75 (USMP-3) Mission Plan

The STS-75 adaptation parameters anticipated a mission of up to 17 days long. In order to make better use of the calibration time, the software was modified prior to STS-73 so that only C-range calibrations would occur in the "Quiet" mode, and calibrations would occur on all three ranges during the "Normal" mode. Since past experience had indicated that the Scale Factor had minimal variations and that, on-orbit, the instrument remains almost entirely in the C-range, the adaptation parameters were selected to use most of the allotted calibration time for C-range bias calibrations in order to obtain the most accurate measurements possible. When operating in the "Quiet" mode, C-range bias calibrations were performed every 158 minutes, but a bias calibration began within one minute after the "Quiet" mode was asserted. A C-range scale factor calibration was performed after every 15th bias calibration in the "Quiet" mode. In the "Normal" mode, a full bias calibration was performed every 432 minutes, and a full scale factor calibration performed after every 6th bias calibration. The calibration plan was to assert the "Quiet" mode when a quiet period could be anticipated. The STS-75

plan did not include any predefined "Quiet" periods in that "around the clock" astronaut operations were planned.

During STS-75, 79 C-range bias measurements were made. Seventeen bias measurements were made on the A and B ranges. There were 13 and 6 scale factor measurements made on the C and A&B ranges, respectively.

2.2 STS-75 Actual Mission Description

Launch for STS-75 was at 3:18 p.m. EST on 22 February 1996. The actual length of the OARE STS-75 mission was nearly 16 days with touch down at 8:58 a.m. EST on 9 March 1996. Shutdown occurred in REENTER mode under the condition of "re-capture duration error" in sub-mode 4. This means that the OARE instrument continued to collect data until the Y-axis signal was saturated for at least 2 minutes in the final REENTER sub-mode. This is considered normal termination of the mission and represents adequate adaptation parameter settings for the reenter file size and correct timing of the reenter discrete.

All engineering parameter values were within normal range. Hardware performance was normal except for the lost of the EEPROM processed data as discussed in Section 2.5.

2.3 STS-75 Data Analysis

This section treats the several analyses carried out on the STS-75 flight data and summarizes the significant results. The processed acceleration data have already been delivered to the Microgravity Measurements and Analysis Branch Program (MMA) at NASA Lewis Research Center.

The Orbital Acceleration Research Experiment (OARE) is designed to measure quasi-steady accelerations from below 10 nano-g up to 25 milli-g where quasi-steady indicates the frequency range from 10^{-5} to 10^{-1} Hz. To accomplish this, the sensor output acceleration signal is filtered with a Bessel filter with a cut-off frequency of 1 Hz. and cut-off rate of 120 dB per decade. The output signal is digitized at 10 samples per second and is then further processed and digitally filtered onboard the OARE instrument with an adaptive trimmean filter prior to the normal EEPROM storage. The trimmean data samples cover 50 second periods every 25 seconds. The regular 10 sample per second data were recorded on the payload tape recorder.

In flight, the OARE instrument is subjected to higher amplitude and higher frequency accelerations (due to the Reaction Control System (RCS) thrusters, structural vibrations and crew activities) in addition to the quasi-steady accelerations due to the gravity gradient, on-orbit drag, slow shuttle body rotations, and long period venting.

In order to obtain the optimum estimate of the quasi-steady acceleration under these conditions, a robust adaptive estimator has been implemented as part of the OARE analysis system. The particular estimator used is known as the Hogg Adaptive Trimmean estimator and is described in Appendix A. The bias estimate using the trimmean estimator of the acceleration is critical to the accuracy of acceleration measurements. During previous missions, the data have been only processed using the trimmean estimator because it provides the best estimate of the quasi-steady acceleration.

However, as a result of the EEPROM write failure, the payload tape recorder data at 10 samples per second became available to Canopus Systems for this mission and has permitted more extensive data analysis.

In the past, it has been the conventional wisdom that the quasi-steady acceleration effects are the most relevant to fluid experiments (as well as others) since these experiments have a finite reaction time and are believed to not to be very sensitive to high frequency accelerations. However, although the structural vibrations and crew activities induce only AC components of acceleration, the thruster firings produce a significant DC component of acceleration even though it is mostly high frequency relative to 0.1 Hz.

For STS-75 (USMP-3) three measures of acceleration have been calculated at the OARE location.

1) The first measure of acceleration is the 50 second trimmean average calculated every 25 seconds as has been done on all previous OARE missions. 2) The second measure is the normal average of 500 measurements of acceleration obtained at the 10 samples per second rate over the same 50 second period as the trimmean measure (sometimes called a top-hat or window average). This measure is also calculated every 25 seconds. 3) The third measure of acceleration is a cosine-squared weighted average of 500 samples of acceleration over the 50 second period. The cosine-squared form is the shape of the finite impulse response filter. In the frequency domain, its 3 dB point is at 0.0144 Hz and has a cut-off of 60 dB per decade. The 50 second trimmean filter is a non-linear filter and largely removes the effect of the large amplitude accelerations due to thruster firings which last a few seconds or less. The regular average and the cosine-squared average filters preserve the DC components of the acceleration.

A detailed discussion of the data analysis undertaken for STS-75 is presented in Appendix A, with particular emphasis the processing filters and the bias estimates using estimated measurement errors based upon the distributions of the measured data. This mission incorporated a full weighted least squares estimate of bias as was done on STS-73. [6]

The complete digital acceleration data presented in this report, as well as the raw payload tape recorder data at 10 samples per second which have not been processed by the filters, are available from the Microgravity Measurements and Analysis Program (MMAP) at NASA Lewis Research Center. [7]

The temperature environment showed some large temperature excursions after the initial thermal pulse generated during launch on STS-75. The instrument temperature in degrees Celsius (measured on the proofmass housing) is shown in Figure 1.

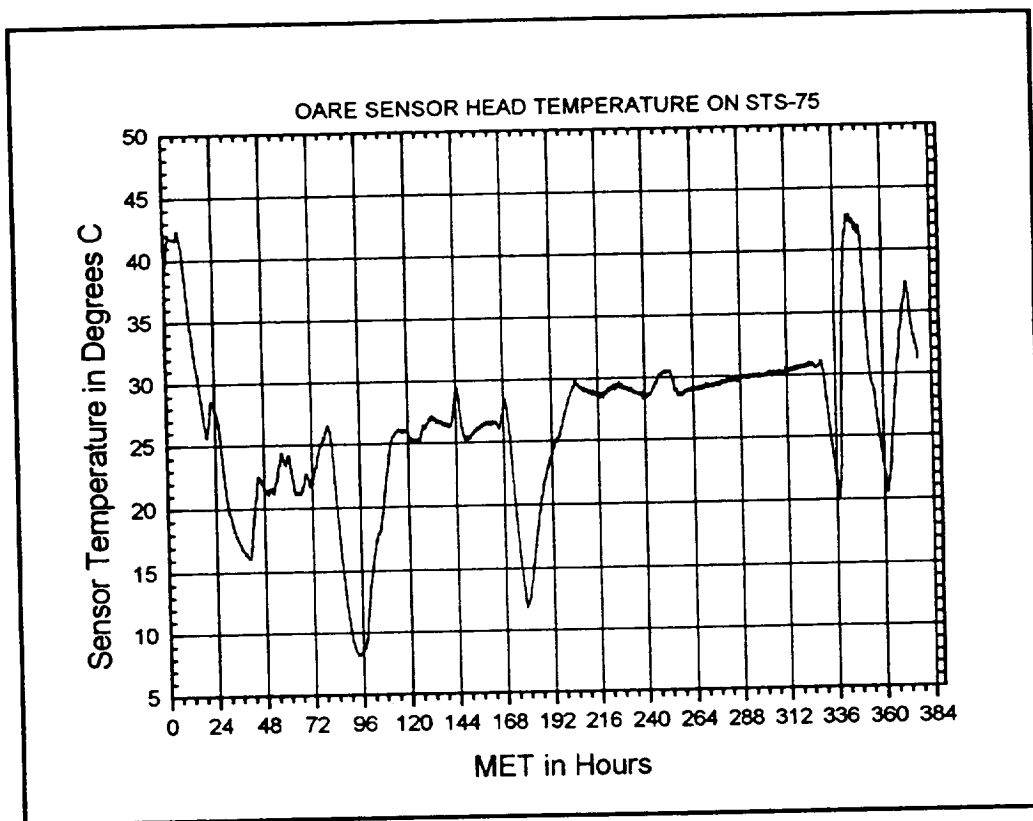


Figure 1. STS-75 Instrument (Sensor Head) Temperature

2.4 Orbiter Body Axis Acceleration Results.

The accelerations measured by OARE at the OARE location in the Shuttle Body Axes coordinate system (X- toward nose, Y -toward the starboard wing, Z -down through the belly) are shown in Figures 2-5 for representative time periods.

Figures 2a, 2b, 2c, and 2d show the trimmean acceleration during the entire mission in segments of 96 hours. This measure of acceleration represents the acceleration due to the quasi-steady forces in that the larger short-period pulses are effectively removed from the data by this filter. The acceleration measurement set has periodic gaps in it as a result of the fact that the measurement data are not being recorded on the payload tape recorder during playback. Also, during bias and scale factor calibrations, the normal acceleration measurements are not being made.

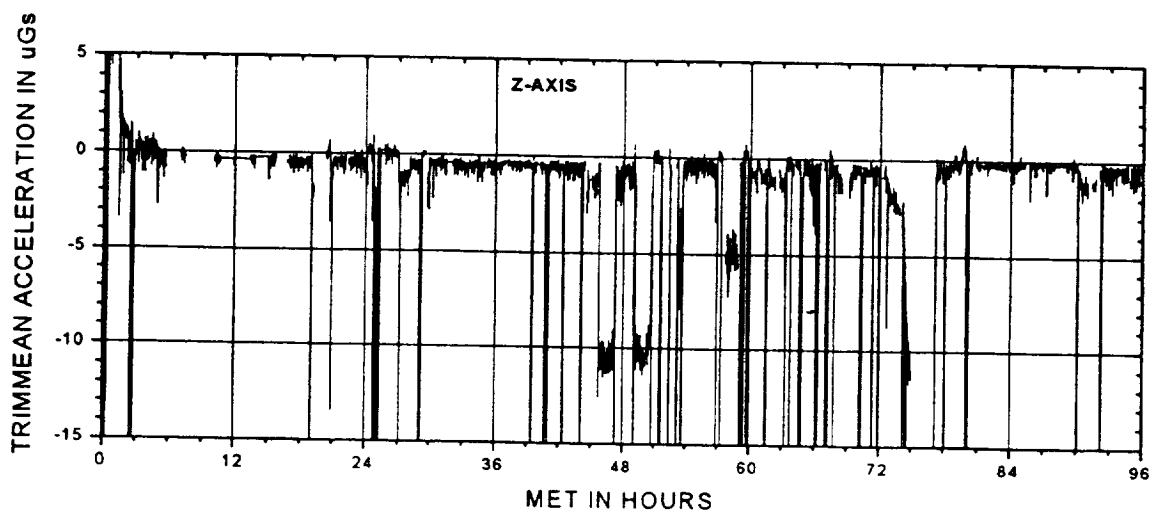
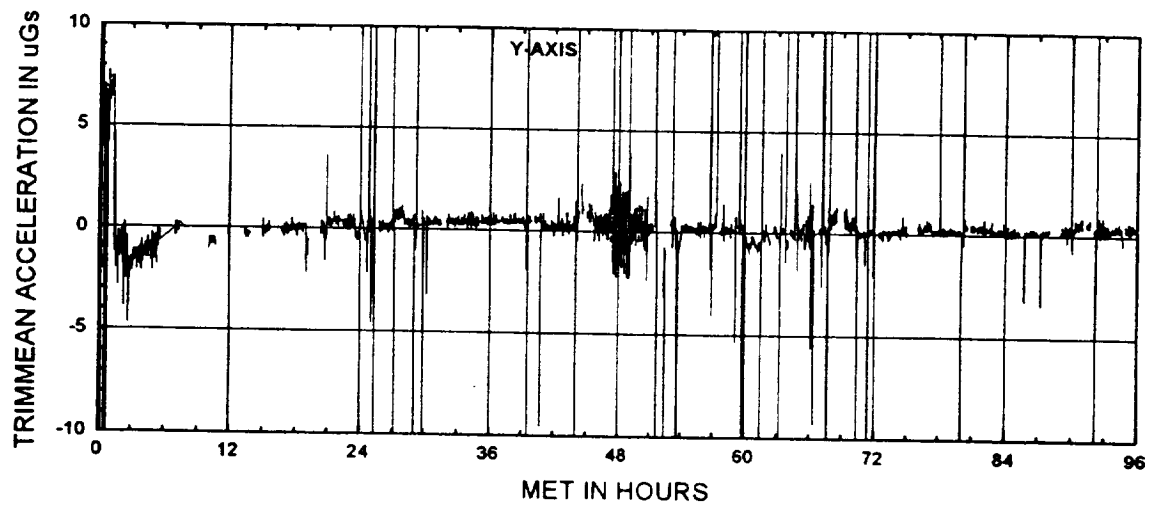
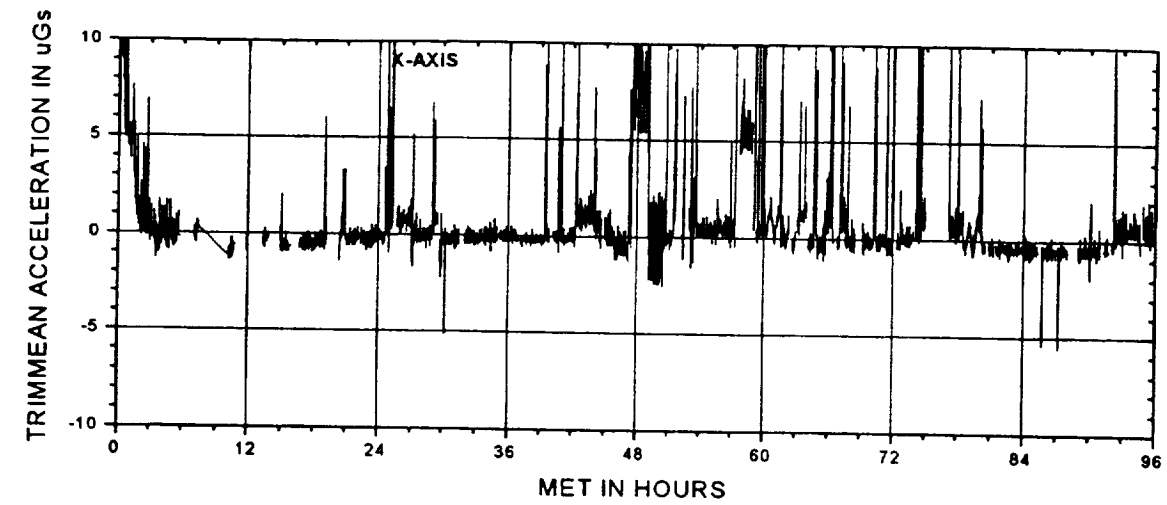


Figure 2a. Trimmean Estimate of the Quasi-Steady Acceleration at the OARE Location.

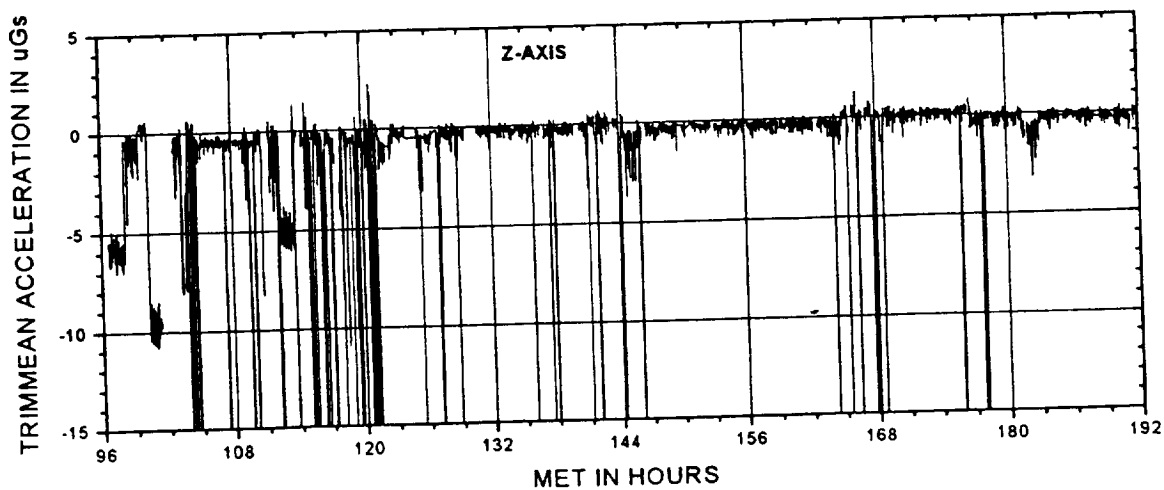
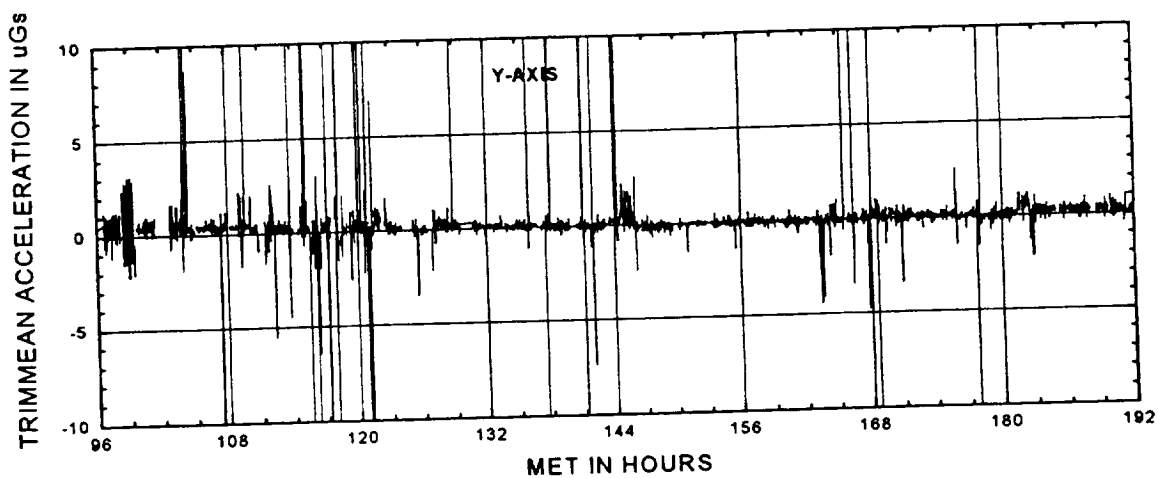
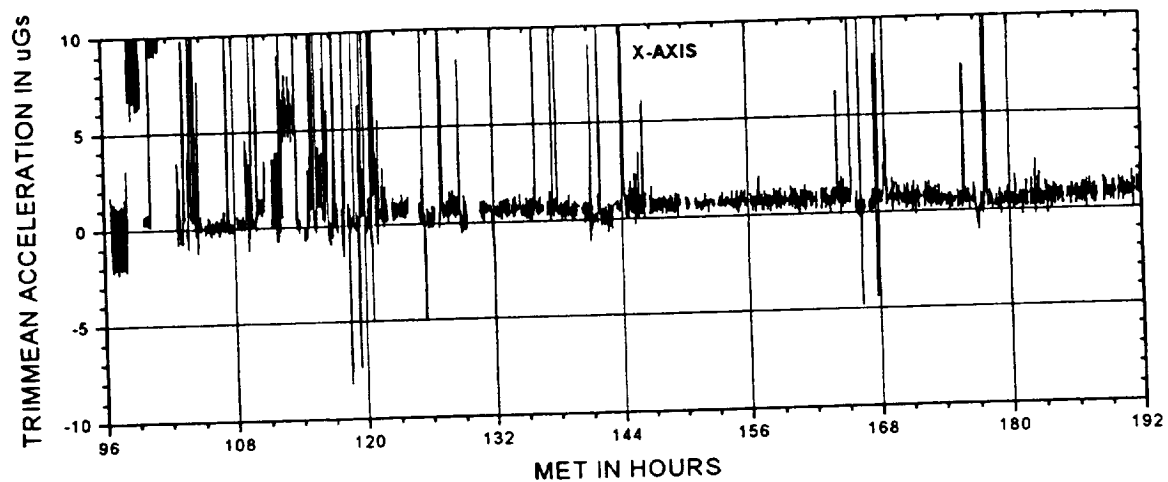


Figure 2b. Trimmean Estimate of the Quasi-Steady Acceleration at the OARE Location.

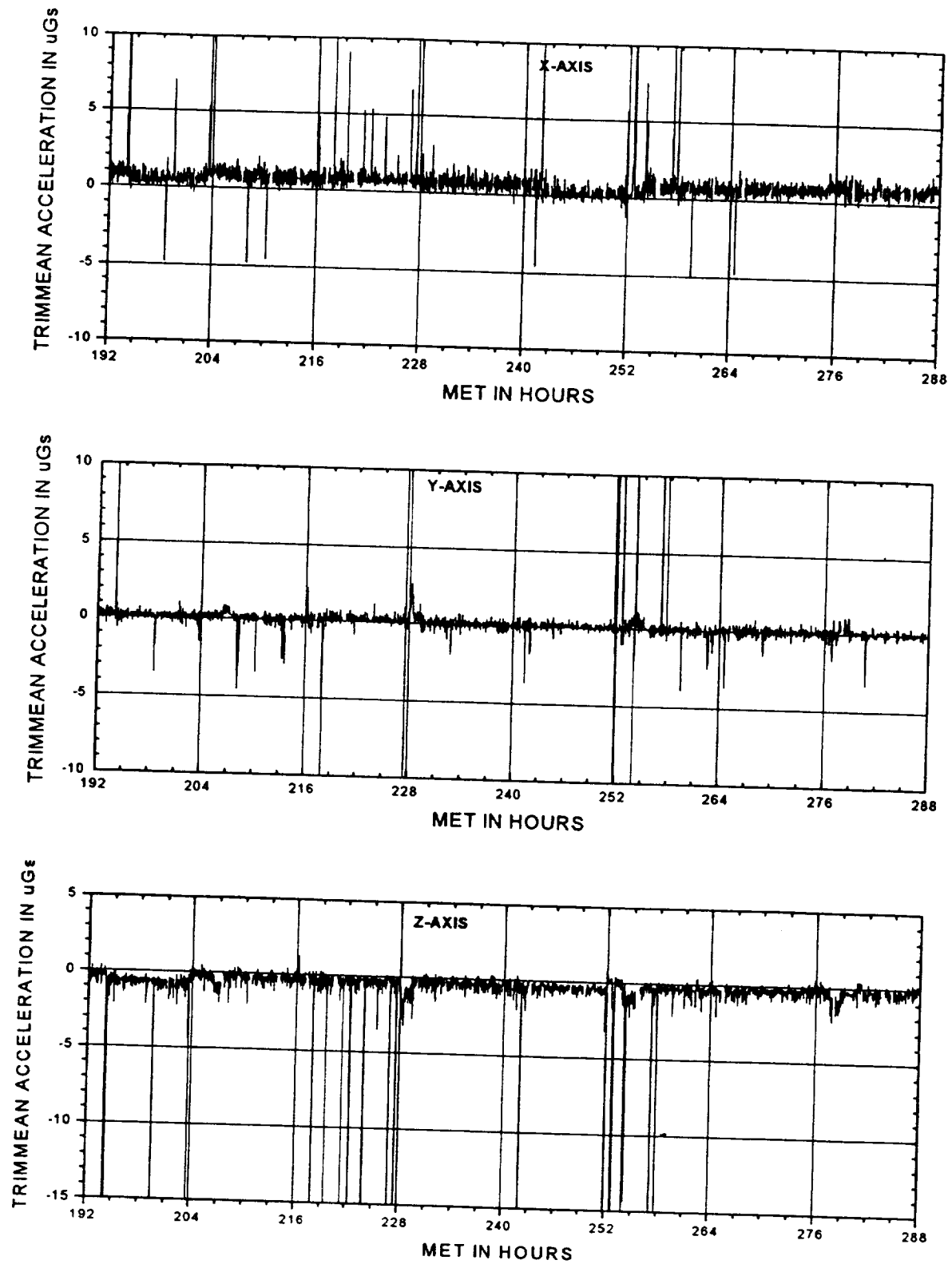


Figure 2c. Trimmean Estimate of the Quasi-Steady Acceleration at the OARE Location.

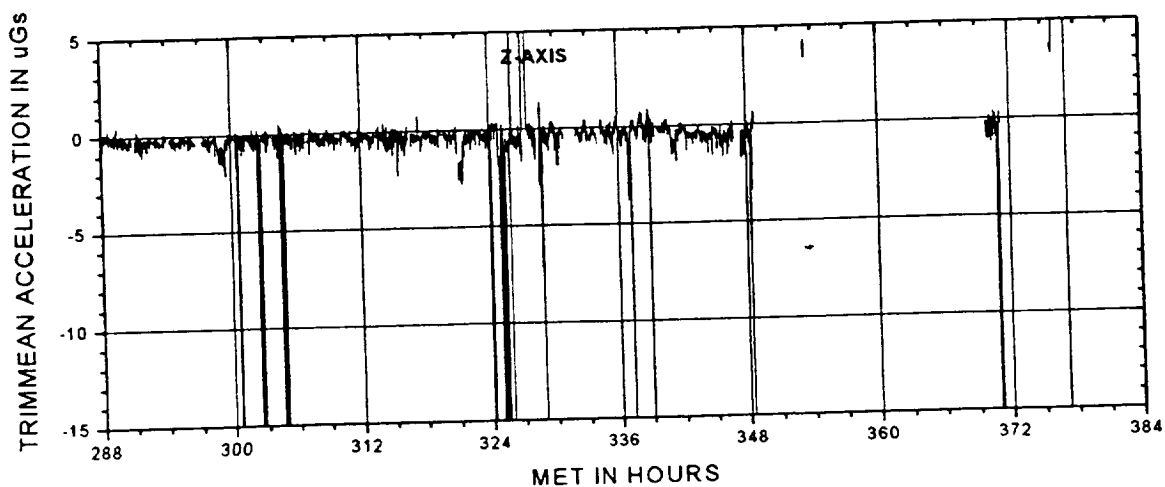
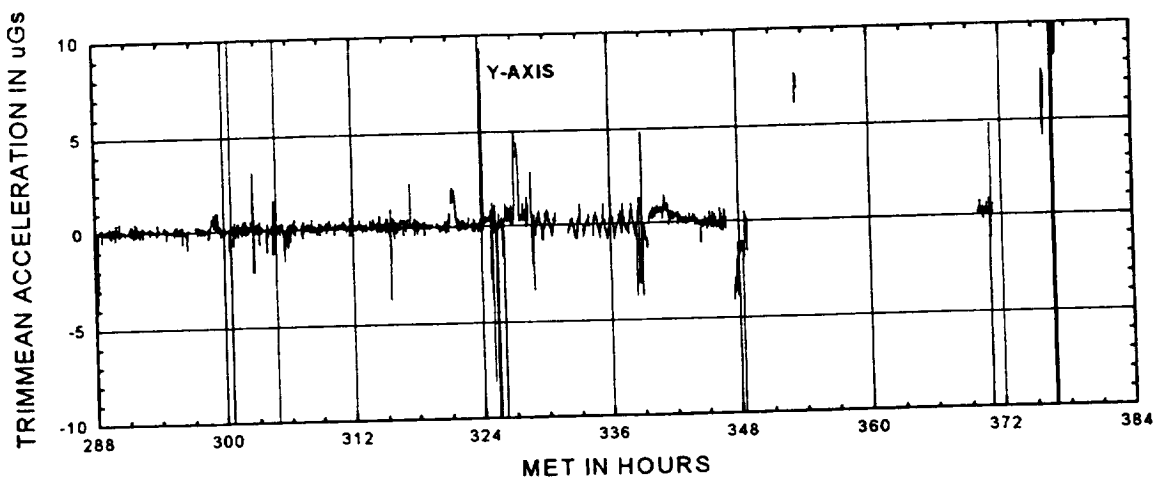
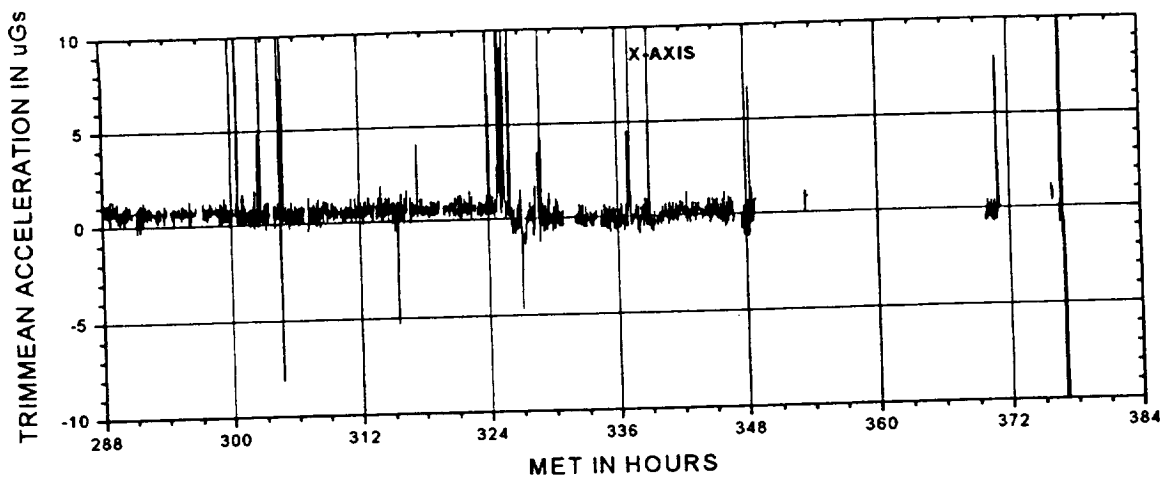


Figure 2d. Trimmean Estimate of the Quasi-Steady Acceleration at the OARE Location.

Figures 3a, 3b, and 3c show the trimmean, regular average, and the cosine-squared filtered acceleration data for the period near MET of 108 hours for the three axes during a quiet period. In these data, the results of processing the raw data by the different filters are similar.

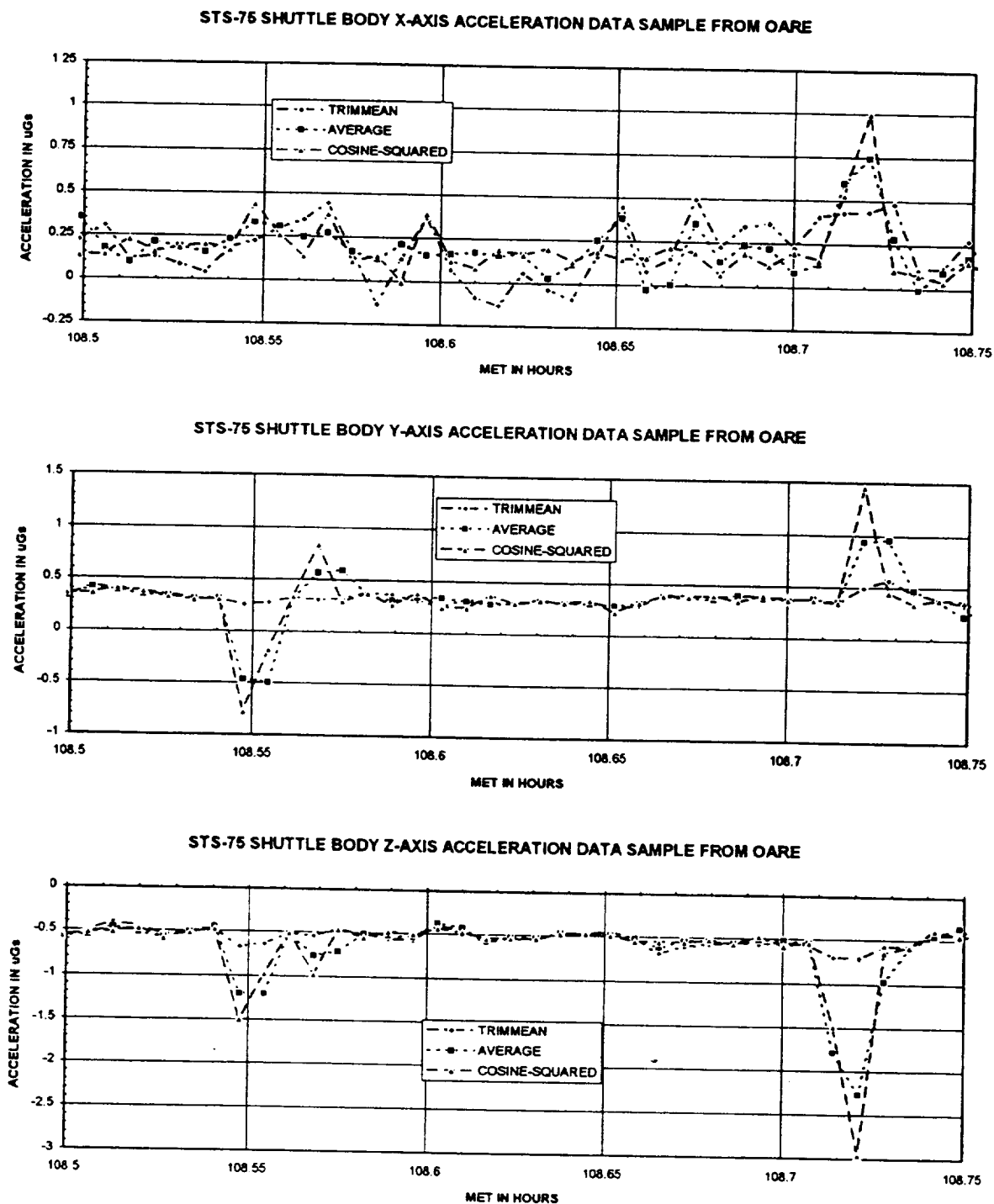
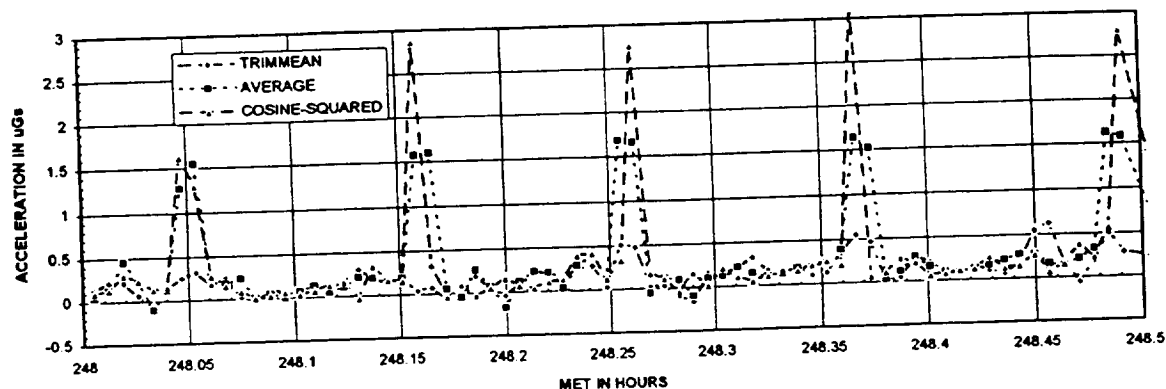


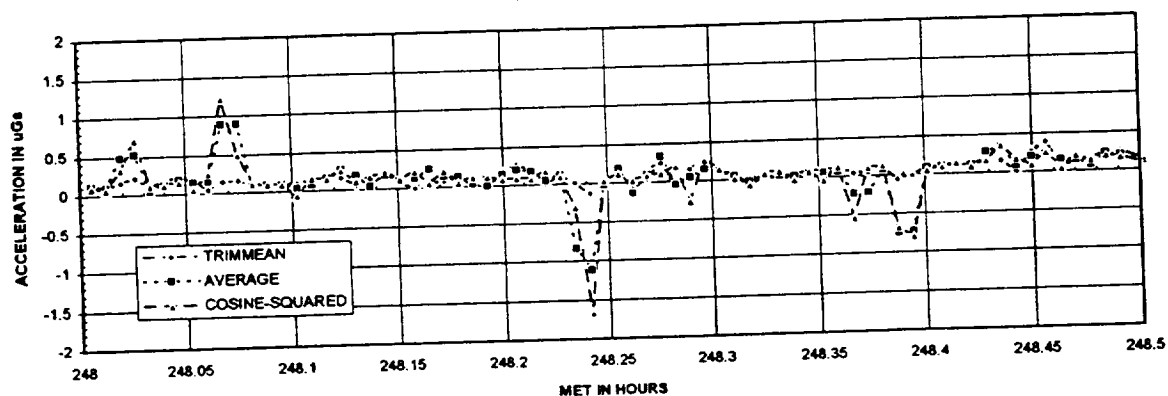
Figure 3. Oare acceleration measurements which show the effect of the processing filters near MET of 108 hours.

Figures 4a, 4b, and 4c are comparable figures near MET 248 hours. This is period where the thrusters are being used to maintain a given attitude. The thruster firings are clearly evident in the average and cosine-squared filtered data, but have been largely removed by the trimmean filter. In this case, the DC average has been changed by the trimmean filter used to measure the quasi-steady acceleration.

STS-75 SHUTTLE BODY X-AXIS ACCELERATION DATA SAMPLE FROM OARE



STS-75 SHUTTLE BODY Y-AXIS ACCELERATION DATA SAMPLE FROM OARE



STS-75 SHUTTLE BODY Z-AXIS ACCELERATION DATA SAMPLE FROM OARE

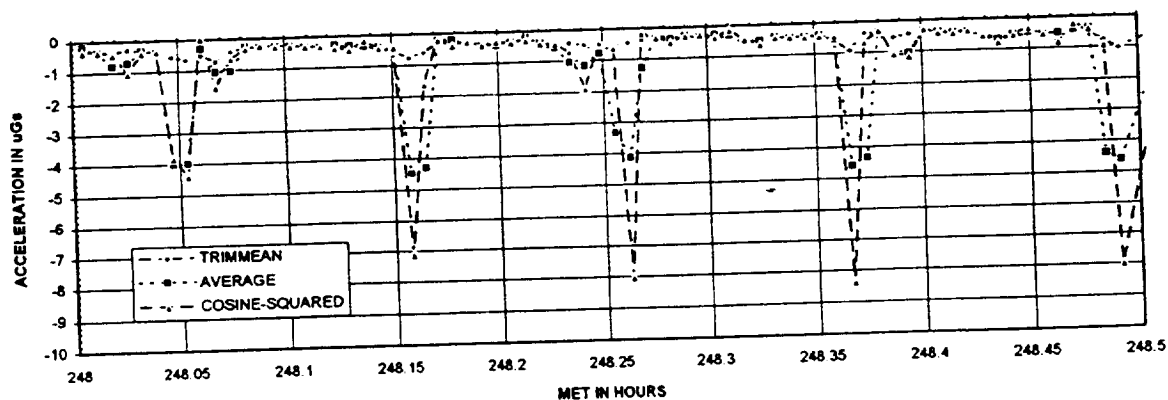


Figure 4. OARE acceleration measurements which show the effect of the processing filters near MET of 248 hours.

Figure 5 shows the trimmean acceleration during the TSS deployment and cable break.

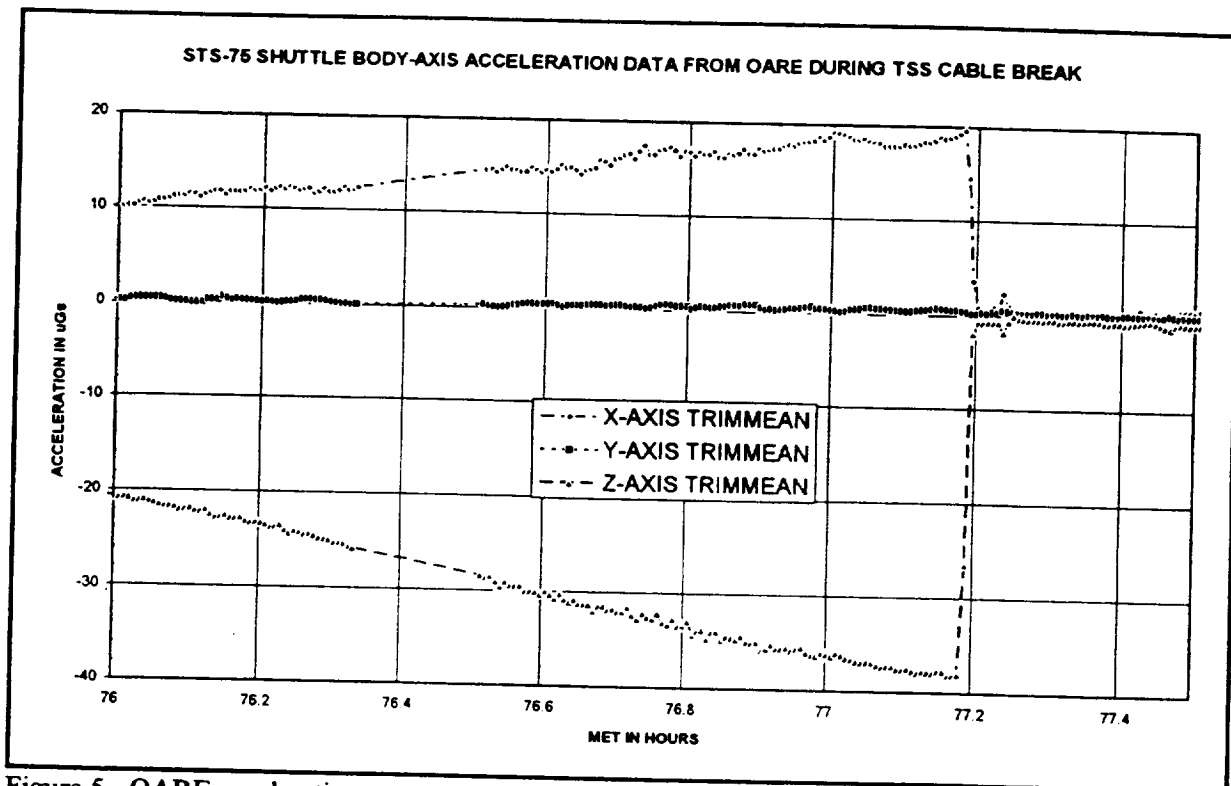


Figure 5. OARE acceleration measurements during TSS cable break.

These figures are a sample of the acceleration data from STS-75 (USMP-3) at the OARE location. However, it is not feasible to present the data with sufficient time and amplitude resolution to meet the requirements of each experimenter in a single report. For additional detail, the complete set of data is available from the PIMS Group at Lewis Research Center. [7] The low frequency accelerations can also be calculated at the experimenters location by the PIMS group using the OARE measurements and other shuttle parameters.

2.5 STS-75 Anomalous Performance

On STS-75 there were anomalies. The first had been seen on previous missions and was not considered significant enough to fix at that time. The second was new to this mission. The following is a discussion of these anomalies.

OARE Z Axis Scale Factor Anomaly

OARE's performance on STS-75 was similar to that on STS-73, STS-65 and STS-62. The Z-axis C-range scale factor calibration was still affected by jitter to a small degree. In addition, the OARE instrument in the C-range continued to show the characteristics of an "electronic bias shift" that was first noted in STS-58 [4]. The electronic bias shift manifested itself with small changes in the pre- and post-rate levels during the scale factor calibration on the Z-axis in the C-range. This electronic bias shift was not apparent in the bias calibrations and appears to be an artifact that occurs only during the scale factor calibration period and, hence, does not affect the Z-axis data collection.

EEPROM Write-Error

The data downloaded from the tape recorder during the mission appeared nominal. However, upon the download of the processed acceleration data stored on the EEPROM at the end of the mission, it was discovered that it was invalid and nearly constant in time. After a post-mission investigation, it was concluded that the write fault was a result of the interaction between some changes in the adaptation parameters and the size of arrays in the software. The effect was reproduced in post-mission testing, and appropriate changes were incorporated for future missions. Only the normal processed data file was affected. The engineering, scale factor, and re-enter files on the EEPROM were normal.

3.0 OARE ACCURACY ANALYSIS

The OARE instrument provides high resolution measurements of sensor input axes accelerations, 3.05 nano-Gs in the OARE X-axis and 4.6 nano-Gs for the Y and Z axes. The accuracy of these measurements is primarily determined by the degree to which the instrument can be calibrated over the time period of the measurements. Major sources of potential errors are the accuracies obtainable from the bias and scale factor calibrations.

3.1 Bias Errors

On STS-75, the bias was measured 79 times. From these measurements, the true bias was estimated by the fitting procedure discussed in Appendix A. Potential errors in these bias estimates arise from the statistical nature of the bias measurements as well as from potential systematic errors which have not been identified. Based upon the analysis contained in Appendix A, we estimate that the bias errors are approximately 50 nano-Gs. These are consistent with the earlier analysis contained in the STS-65 Final Report [5].

3.2 Scale Factor Errors

In the microgravity environment of the Orbiter, the quasi-steady trimmean acceleration measurements are typically on the order of 1 micro-g or less. Under these conditions, the bias errors are larger than the scale factor errors.

Measurements of the scale factors made during flight and those on the ground are now consistent to within 1 to 2 percent. We estimate the scale factor errors to be about 1 to 2 percent of the measured acceleration. These could be reduced with further study. At a 1 micro-g level, this corresponds to a 10 to 20 nano-G error. These should be added in quadrature with the bias errors. So overall, this gives estimated errors for the on-orbit acceleration measurements of about 50 to 60 nano-Gs.

3.3 Quasi-Steady Acceleration Measurements

As indicated, the primary OARE data recorded on the flight computer is processed through an adaptive trimmean filter. This trimmean filter provides a near optimum estimate of the mean of the quasi-steady acceleration population of measurements over the 50 second sampling period. This estimate is particularly beneficial in the calculation of the bias estimate and the estimate of the quasi-steady acceleration due to orbital drag, gravity gradient, and slow body rotations. However, it tends to reject the effects of crew activity, thruster firings, and other exogenous events. Because many experimenters may be interested in the regular average of the acceleration measurements over the 50 second sample period, we processed the measurements from this mission also with the DC level preserving regular average and the cosine-squared filters. We are now considering incorporating the regular average as well as the trimmean average for the sampling periods into the

data recorded on the flight computer . In any case, the regular average and other filters can be applied to the telemetry and payload tape recorder data for those periods where the data exists.

4.0 REFERENCES

- 1) R.V. Hogg, "Adaptive Robust Procedures: A Partial Review and Some Suggestions for Future Applications and Theory," Journal of American Statistical Association, Vol. 69, Number 348, December 1974, pp 909-927.
- 2) T. DeWet, J.W.J. VanWyk, "Efficiency and Robustness of Hogg's Adaptive Trim Means," Commun. Statist.-Theor. Meth., A8(2), pp 117-128, 1979.
- 3) "STS 62 Final Report," OARE Technical Report #145: Canopus Systems, Inc., July 1994.
- 4) "OARE Flight Maneuvers and Calibration Measurements on STS-58," NASA TM-109093, R.C. Blanchard, J.Y. Nicholson, J.R. Ritter, K.T. Larman, April 1994.
- 5) "STS-65 Final Report," OARE Technical Report #146, Canopus Systems, Inc., November 1994.
- 6) "STS-73 (USML-2) Final Report," OARE Technical Report #147, Canopus Systems, Inc., February 1996.
- 7) Microgravity Measurement and Analysis Program (MMAP) at Lewis Research Center. Program Scientist of Principle Investigator of Microgravity Services (PIMS) is Richard Delombard, (216) 433-5285. E-mail to richard.delombard@lerc.nasa.gov. Data file server is beech.lerc.nasa.gov.

APPENDIX A OARE DATA CALIBRATION AND PROCESSING

This Appendix reviews the methods used to calculate the Orbiter body triaxial acceleration based on the raw OARE instrument measurements which were recorded on the payload tape recorder, downloaded, and then processed by Canopus Systems. The method of estimating the sensor bias has evolved over the past several missions; STS-73 was the first mission where a full weighted least squares methodology has been implemented in estimating the instrument bias. The Appendix begins with the instrument model (A1), discusses the filters (trimmean, regular average, and cosine-squared average) used in processing the raw OARE accelerometry data (A2), presents the weighted least squares estimate of the bias of the instrument (A3) and finally presents a short discussion of Scale Factor calibration (A4).

A1 INSTRUMENT MODEL

The OARE instrument acceleration for each axis and range is calculated from an equation of the form

$$A_A = -SF_C * SF_N * (CTS - 32768 - BIAS) \quad (\text{eq. 1}), \text{ where}$$

A_A is the calibrated actual acceleration in uGs,
 SF_C is the Scale Factor Calibration term,
 SF_N is the Nominal Scale Factor in uGs per count,
 CTS is the counts out of the instrument A/D converter, and
 $BIAS$ is the estimated Bias in counts as a function of time and temperature,
where each of the terms is dependent upon the particular axis and range.

In the above equation, the number 32768 appears because the 16-bit A/D converter is single-ended; this value is the offset required to obtain a zero measured acceleration for a zero input acceleration when there is no bias.

An Actual Scale Factor SF_A term is defined by

$$SF_A = SF_C * SF_N \quad (\text{eq. 2}).$$

Values of the nominal scale factor, SF_N , are given in Table 1 of the main report for each OARE axis and range. Values of SF_C for the OARE X, Y, and Z axes are approximately 1.02, 1.11, and 1.10, respectively, but are determined through calibration on each STS mission for each axis and range.

The output of the A/D converter provides a raw digital acceleration data sample which is effectively processed at a rate of 10 times per second. Data are normally stored on the EEPROM at a rate of once every 25 seconds, and these data represent the trimmean filtered estimate of the quasi-steady acceleration value over a 50-second period. The data presented in this report are based upon post processing the raw 10 sample per second data from the payload tape recorder through three separate filters.

A2 FILTERS USED IN PROCESSING OARE ACCELERATION MEASUREMENTS

The OARE instrument is designed to measure the quasi-steady acceleration from below 10 nano-Gs up to 25 milli-Gs and over the quasi-steady bandwidth from 10^{-5} to 10^{-1} Hz. The quasi-steady acceleration components of primary interest are those due to gravity gradient, on-orbit drag, inertial rotations, and perhaps long period venting or gas leaks. However, the instrument is subjected to higher amplitude and higher frequency accelerations (such as structural vibration, station keeping thruster firings, and crew effects) in addition to the quasi-steady accelerations. These higher level accelerations are not well characterized nor statistically invariant over the OARE measurement periods.

On past missions, the OARE data has been processed on-board using only a non-linear trimmean filter. This filter has the characteristic of effectively removing large amplitude short-period pulses due to thruster firings from the average. The remaining acceleration is effectively due to the quasi-steady forces. However, on this mission since the on-board processed trimmean processed data were lost, the raw data were processed to obtain the acceleration. In addition to the trimmean processing, 50 second regular averages and a 50 second cosine-squared weighted averages were calculated.

A2.1 Hogg Adaptive Trimmean Filter

In order to obtain a more optimum estimate of the quasi-steady acceleration under the conditions of intermittent thruster firings and crew activities, a robust adaptive estimator has been implemented. For a discussion of robust estimators, see Reference 1. The particular estimator implemented in OARE is known as the Hogg Adaptive Trimmean estimator and is described in more detail in Reference 2.

In essence, the trimmean adaptive filter removes a percentage of the distribution from each tail and then calculates the mean of the remaining distribution. It first measures the departure of the sample distribution from a normal (Gaussian) distribution as measured by a parameter called Q , then adaptively chooses the amount of the trim to be used on the distribution, and finally calculates the mean of the remaining distribution after the trim. This filter is designed to remove the effect of a contaminating distribution (such as a thruster firing) superimposed on a normal distribution (of instrument noise, high frequency vibrations, crew activities, quasi-steady accelerations, etc.),

As implemented, Q is defined by the following equation:

$$Q = [U(20\%) - L(20\%)]/[U(50\%) - L(50\%)] \quad (\text{eq. 3}), \text{ where}$$

$U(X\%)$ is the average of the upper $X\%$ of the ordered sample, and
 $L(X\%)$ is the average of the lower $X\%$ of the ordered sample.

In the OARE case, the ordered sample has been a sample of 500 acceleration measurements of the A/D output over a 50-second measurement period.

Q is a measure of the outlier content in the sample. For a Gaussian distribution, Q is 1.75; for samples which have larger tails, $Q > 1.75$. The value of Q is used to estimate the extent that the quasi-steady acceleration measurements may be contaminated by thruster firings, crew activities, etc.

In order to improve the estimate of the quasi-steady acceleration, a trimmean is used to estimate the mean of the quasi-steady population. A trim parameter alpha is determined by the following algorithm:

$$\alpha(Q) = \begin{cases} 0.05 & \text{for } Q \leq 1.75 \\ 0.5 + 0.35 * (Q - 1.75) / (2 - 1.75) & \text{for } 1.75 < Q < 2.0 \\ 0.4 & \text{for } Q \geq 2.0, \end{cases} \quad (\text{eq. 4})$$

where alpha is the fraction of the distribution which is trimmed off each tail of the ordered distribution before the mean of the remainder of the distribution is calculated.

Then, for an underlying distribution of n points or measurements with a value of alpha, the trimmean is given by

$$\text{trimmean} = [X_{(k+1)} + X_{(k+2)} + \dots + X_{(n-k)}] / (n - 2 * k), \quad (\text{eq. 5}),$$

where $k = \alpha * n$ (eq. 6) and

$X_{(i)}, X_{(i+1)}, \dots, X_{(n)}$, is the ordered set of n points making up the sample distribution.

In summary, OARE measures the quasi-steady level of acceleration for each axis every 25 seconds by taking the trimmean of 50 seconds of A/D counts (500 samples in total) according to equations 3 through 6, and then substituting this trimmean for CTS in equation 1. It should be noted that for large pulses in one direction, the effect of the trimmean is to shift the estimate of the mean; it does not preserve the DC component in this case.

The trimmean is particularly appropriate for estimating the bias of the OARE instrument, since one wishes to remove the effect of the thruster on the bias measurement if a thruster firing should occur during the bias measurement period.

Data normally recorded on the EEPROM (but not recorded there on STS-75) and available to support the acceleration calculations include the trimmean of the 50-second distribution every 25 seconds, the Q of this sample distribution, the Average Deviation from the trimmean of the distribution used to calculate the trimmean, the instrument temperature, the Mission Elapsed Time (MET), and numerous housekeeping parameters. On STS-75 these parameters were recalculated from the payload tape recorder data. In addition, the regular average and the cosine-squared weighted average were calculated for STS-75.

The widths of the 500 sample distributions (as measured by the standard deviations) are almost entirely due to the environment aboard the shuttle and not due to sensor noise. This is illustrated in Figure A-1, where the trimmean counts for the OARE X-Axis is plotted for MET from 54 to 72 hours on STS-62 [3]. On STS-62, the whole crew had common sleep

periods as can be noted by the small variation in the data obtained during a sleep period from about 59 to 65 hours. During this period, the instrument output is extremely quiet as opposed to periods when there is crew activity. On STS-65 and later missions, the crew has been active 24 hours per day and consequently noisier data from a quasi-steady point-of-view resulted.

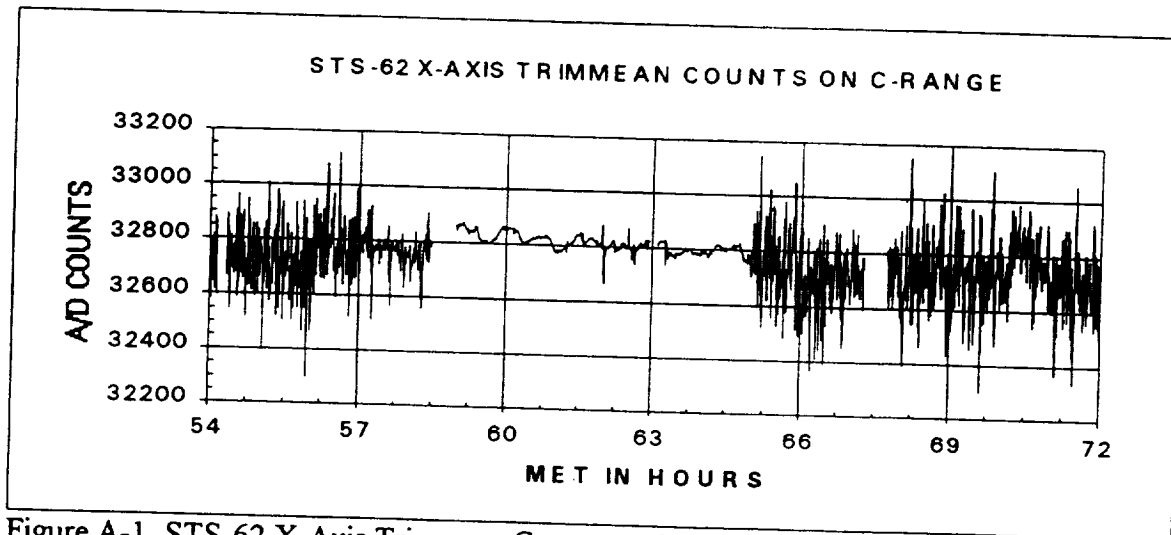


Figure A-1. STS-62 X-Axis Trimmean Counts on C-Range showing a sleep period.

A2.2 Regular (Top-hat or Window) Average

In addition to the trimmean average, regular averages for the same 50-second periods as the trimmean were calculated on STS-75. The regular average consists of the average of the 500 measurements which were made during the 50 second averaging period. These averages were calculated at 25 second intervals, the same as for the trimmean. For the cases where there were not 500 measurements after the last average because of a range change or the beginning of a calibration sequence, the average was done using the available data points.

A2.3 Cosine-squared Average Filter

Also, a cosine-squared average filter was used to process the 10 sample per second raw data. The cosine-squared filter acts as a line spread weighting function in the form of a cosine-squared function which is 0 at point 1 and point 500 for the 50-second sample period and is normalized to 1. It effectively has a 3dB cut-off at 0.0144 Hz and a roll-off of 60 dB per decade. This filter has a sharper roll-off and a larger finite impulse response than the regular 50-second average filter. This filter was applied to the same sample sets as the trimmean and average filters. For sample sizes less than 500, the weights of the filter multipliers were appropriately changed.

A.2.4 Example of Raw and Filtered Data

Figure A.2 shows the effect of the filters when applied to the raw 10 sample per second data. For the OARE Y-axis, the bandpass is about 0.16 Hz. As shown, the raw data shows a peak-to-peak excursions of about 3000 counts or about 15 micro-Gs. However, sometimes there

are significantly larger pulses--probably due to thruster firings. These larger pulses are treated differently by the filters. As can be seen, the pulse at about 25412 seconds is effectively removed by the trimmean filter and is not apparent in this filtered data. For the 50-second average data, this pulse just generates a square wave as it passes through the 50 second window. For the cosine-squared filter, the impulse effectively generates the shape of the cosine-squared filter lineshape. Thus, for the period around the large pulse, the various filters give different results. The trimmean filter has effectively removed the large amplitude pulse and has changed the DC average during the period around the pulse. The window average filter and the cosine-squared average filter spread the pulse out over a longer time period so that the data can be sampled at a lower rate and do not change the total DC average around the pulse. For regular data without "significant" pulses, the DC levels or outputs of the filters are generally the same. One should note that in the figure, the filtered data is presented at 10 times per sample, but in the real processed data, the filter operates only every 25 seconds--corresponding to the vertical grid lines in the figure.

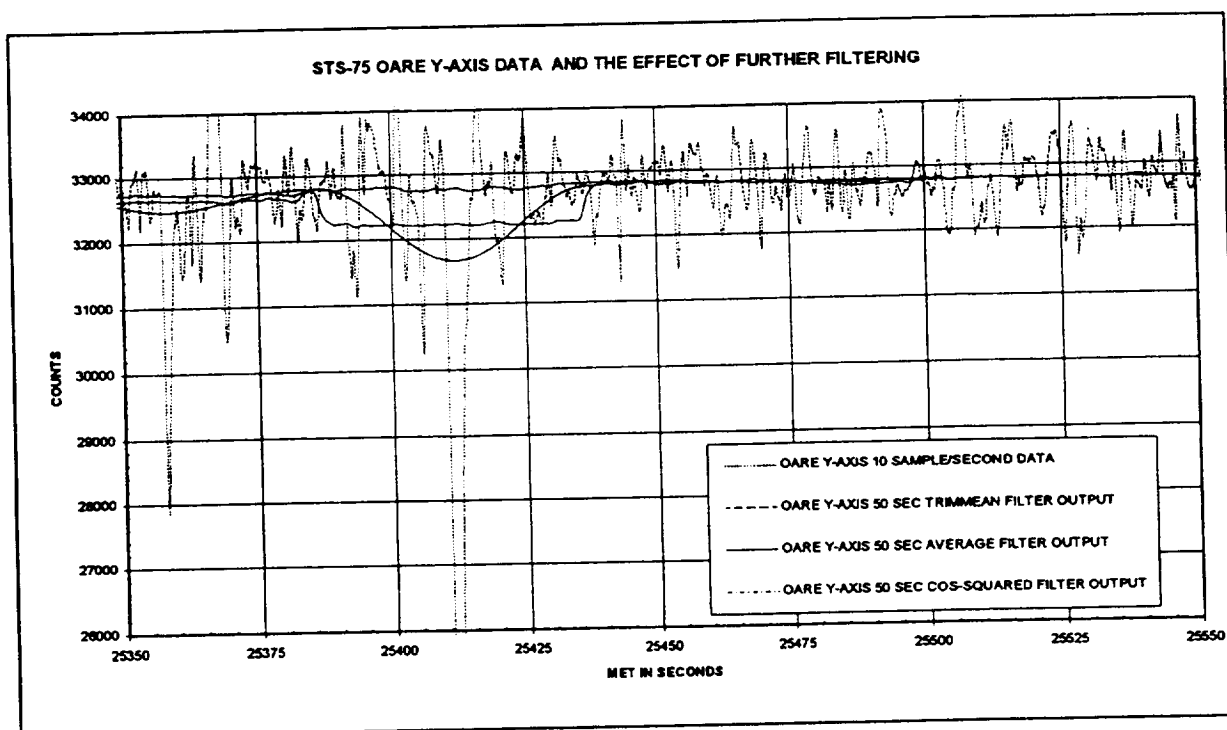


Figure A.2 OARE Raw and Filtered Y-Axis Data--An Example.

A3 BIAS MEASUREMENTS AND ESTIMATED MEASUREMENT ERRORS

As can be seen in Equation 1, the calculated acceleration depends upon the instrument bias. This is a critical parameter in accelerometers that are designed to measure quasi-steady or DC accelerations below 1 milli-G. For on-orbit conditions, the typical quasi-steady or DC acceleration is less than 1 micro-G. Thus, the bias estimate is absolutely critical to accurate acceleration measurements in this regime.

The OARE accelerometer uses an electrostatically suspended proofmass in order to minimize the effects of temperature and mechanical suspension hysteresis on the bias. In addition,

OARE incorporates a two-axis gimbal calibration table by which the OARE instrument can be calibrated on-orbit for bias and scale factor in each of its three axes.

A3.1 Bias Measurements

The bias measurement for a single axis consists of the following sequence: 1) measuring the acceleration output in trimmean counts for 50 seconds in the normal table position for a given axis (called $BIAS_N$), 2) rotating the input axis 180° , and then 3) measuring the acceleration output in trimmean counts (called $BIAS_I$, for inverted position). Assuming that the actual input acceleration remains constant during this period (about 125 seconds), as might be expected for quasi-steady accelerations, then the bias can be calculated by

$$BIAS_M = (BIAS_N + BIAS_I)/2 - 32768 \quad (\text{eq. 7}), \text{ where}$$

$BIAS_M$ is the measured bias for a particular axis,
 $BIAS_N$ is the bias measurement in the normal position, and
 $BIAS_I$ is the bias measurement in the inverted position.

During a single mission, the bias is measured for each axis many times for the C-range. These bias measurements then provide the basis for estimating the bias time history throughout the mission. The bias estimates are ultimately determined by fitting a functional form through these bias measurements.

A3.2 Sources of Noise Associated with the Bias Measurement

The sources of noise which contribute to measurement errors on the bias measurements are largely associated with crew activity, as indicated in Figure A-1. The bias measurement accuracy depends upon the input acceleration remaining constant during the time that the bias measurements are being made. The time difference between the two positions used in the bias measurements is about 75 seconds--corresponding to every 3rd measurement point in Figure A-1. Clearly, the input acceleration is varying except during the times when the whole crew is asleep. During most missions, one segment of the crew is active at all times--as was the case on STS-75. Under these conditions, the bias measurements contain significant measurement errors which cannot be eliminated. A method of estimating the measurement errors on the bias has been developed and is discussed in Reference 5.

A3.3 Bias Estimates Based Upon Weighted Least Squares Fits

The bias was measured 79 times on STS-75 for each of the three axes on the C-range. Using the methodology discussed in Reference 5, estimates of the measurement errors associated with each bias measurement were calculated. The results for the OARE X, Y, and Z axes are shown in Figures A-3, A-4, and A-5, respectively. The bias measurements are shown along with their associated measurement error bars.

As can be seen, there is considerable variation of the individual bias measurements, but the variation is generally explained by the measurement errors associated with the bias

measurements. There are a few bias measurements which are widely separated from the others. These could be a result of thruster firing during the bias sequence.

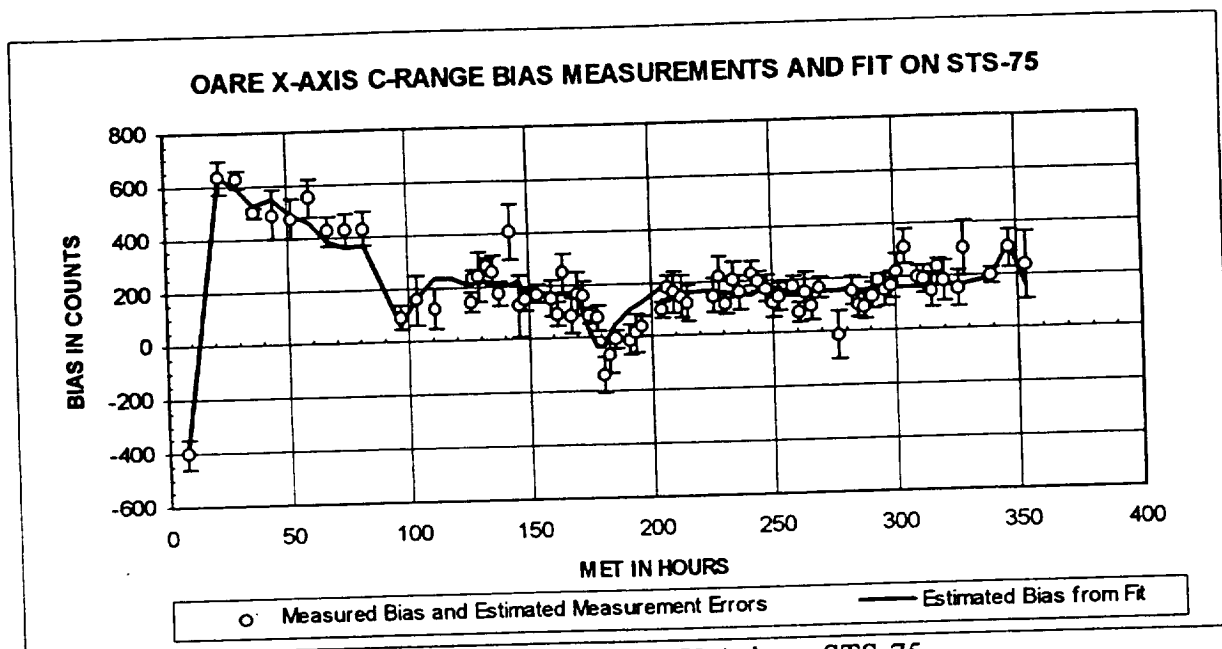


Figure A-3. Bias Measurements and Fit for OARE X-Axis on STS-75.

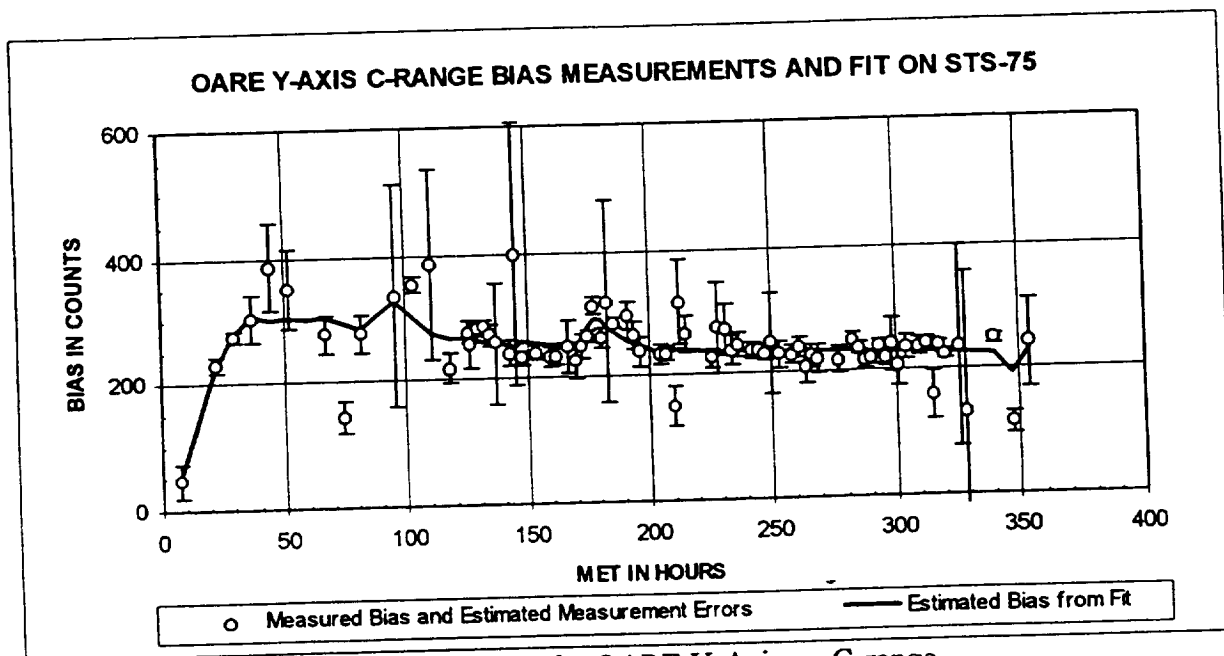


Figure A-4. Bias Measurements and Fit for OARE Y-Axis on C-range.

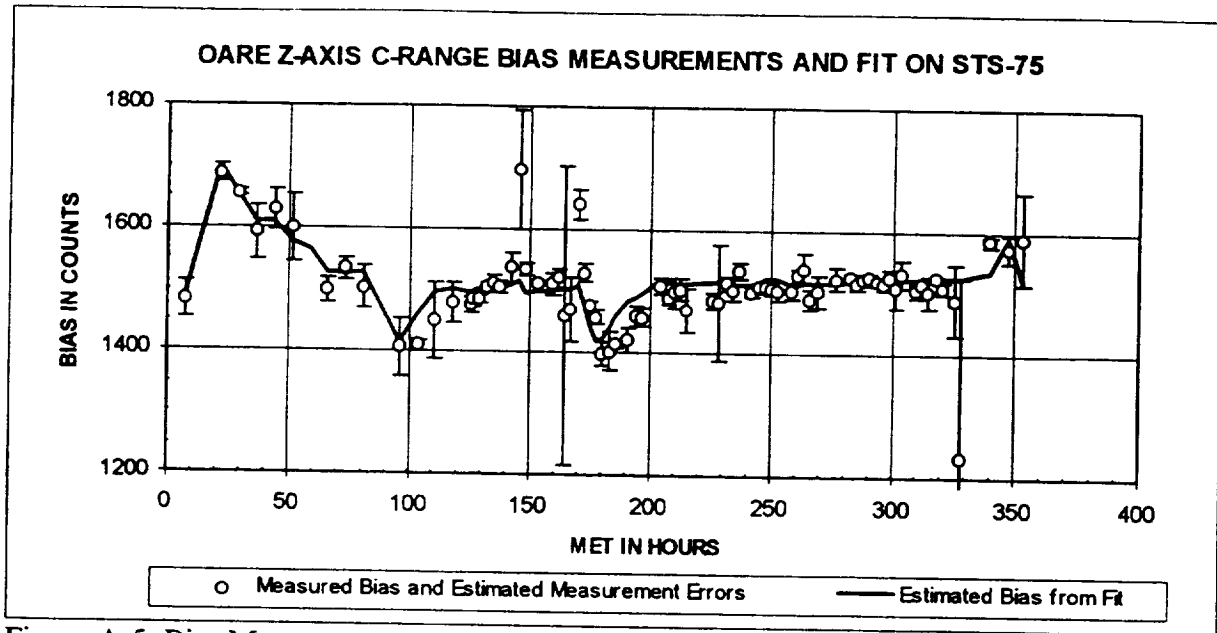


Figure A-5. Bias Measurements and Fit for OARE Z-Axis on C-Range.

The bias can be characterized by an initial transient after launch as a function of time and a small dependence upon temperature. In the same manner since STS-62 [3], we have fitted the measured bias data with a function of the following form:

$$\text{Bias} = A_1 + A_2 * e^{-(t/t_0)} + A_3 * e^{-(t/t_1)} + A_4 * T \quad (\text{eq. 8}),$$

where A_1 , A_2 , A_3 , A_4 , t_0 and t_1 are fitted coefficients, t is the mission elapsed time in hours, and T is the instrument temperature in degrees Celsius.

A weighted least squares procedure was used to determine the coefficients for the C-range. As part of the fitting procedure, several data points (1, 9, and 7 for the X, Y, and Z axes, respectively) which were significantly off the fitted curve, i.e., 2 standard deviation effects, were removed from those included in the fit and the fitting procedure was repeated for the C-range fits. Also for the B and A ranges, a weighted least squares procedure was used. Results from these fits are shown in Table A-1.

The bias calculated by equation 8 is then used to estimate the actual bias during the mission as a function of MET and instrument temperature. This bias is then used to calculate the actual acceleration using equation 1. We believe that the error in the acceleration measurements associated with this bias estimation procedure is about 50 nano-Gs. The error could be further reduced if there were more quiet periods during the mission when a low noise bias calibration could be performed.

A4 SCALE FACTOR CALIBRATION

Scale factor measurements are made by applying a known non zero signal to the sensor and electronics for each channel and each range. These measurements may be contaminated by noise in the external environment or by internal noise in several forms.

Table A-1. STS-75 Bias Fits to EEPROM Data.

STS-75 BIAS FITS TO EEPROM DATA			
OARE X-AXIS			
	A	B	C
Range	17.07	-11.93	-259.34
Fitted Constant A1	9.89	109.23	1148.80
Fitted Constant A2	0	-450.94	-4414.76
Fitted Constant A3	0.167	1.132	13.694
Fitted Constant A4	172.5	58	56
Fitted Constant to	none	7.7	7.9
Fitted Constant t1			
Standard Deviation of Fitted-Measured	1.06	6.36	64.3
R-Squared of Fit	0.994	0.987	0.921
Number of Measurements	16	15	78
OARE Y-AXIS			
	A	B	C
Range	3.60	47.30	321.54
Fitted Constant A1	15.71	-16.29	189.79
Fitted Constant A2	0	0	-456.64
Fitted Constant A3	-0.777	-1.114	-3.068
Fitted Constant A4	700	17	58
Fitted Constant to	none	none	18.7
Fitted Constant t1			
Standard Deviation of Fitted-Measured	1.30	3.51	33.12
R-Squared of Fit	0.985	0.955	0.988
Number of Measurements	17	15	71
OARE Z-AXIS			
	A	B	C
Range	163.11	186.71	1345.29
Fitted Constant A1	10.26	62.72	1249.21
Fitted Constant A2	0	-115.71	-1884.19
Fitted Constant A3	0.209	0.950	5.793
Fitted Constant A4	28	56.5	22.7
Fitted Constant to	none	10.3	11.7
Fitted Constant t1			
Standard Deviation of Fitted-Measured	1.07	6.50	48.01
R-Squared of Fit	0.999	0.999	0.999
Number of Measurements	16	17	73

For OARE, the method of scale factor calibration involves rotating the Motor/Table Subsystem (MTS) (sometimes called "the table") at a known angular rate ω with a fixed sensor to center-of-rotation offset radius r . The known signal is thus the controlled centripetal acceleration. While collecting scale factor data, the sensor also experiences a bias (assumed constant) and is exposed to an external signal. Data collected before and after the scale factor slew assists in removing the bias and external signal effect.

The basic scale factor measurement model is shown in Figure A-6.

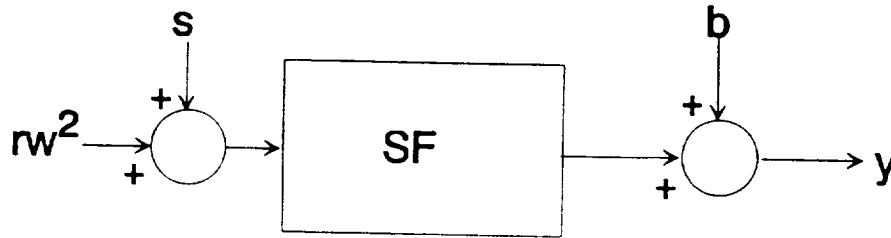


Figure A-6. Scale Factor Measurement Model

From this model, the k^{th} measurement y_k is given by

$$y_k = (r\omega^2 + s_k) / SF_A + b_k \quad (\text{eq. 9}),$$

where s_k is the signal at the k^{th} measurement time and b_k is the internal bias at the k^{th} measurement time. We assume that ω is constant throughout the slew. We also assume that s_k contains two components: (1) an acceleration signal which is fixed with respect to the MTS base throughout the slew and (2) a noise input with zero mean. To eliminate noise, consider averages of the measurements over the data set (with length n)

$$\bar{y} = (r\omega^2 + \frac{1}{n} \sum_{i=1}^n s_i) / SF_A + \bar{b} \quad (\text{eq. 10}),$$

where $(\bar{})$ is the average value of () .

From this equation we can find the actual scale factor SF_A . Here, \bar{y} is the average of the measurements and $r\omega^2$ is known. The remaining unknown, s_k , is a combination of the external signal and noise. This is related to the midpoint measurement (MP). During the slew, the sensor records varying magnitudes of the external signal. The bias and centripetal acceleration, however, remain fixed in magnitude. If the measurements are centered around the midpoint, the midpoint measurement can be used to estimate this external signal and remove it from the scale factor equation. It can be shown that the influence that the external signal and bias have on the scale factor measurements is related to the sinc function $(\sin(x)/x)$ of the angular travel. The actual scale factor can then be found from the following equation:

$$1 / SF_A = \frac{\bar{y} - MP(\sin(\delta) / \delta) - (1 - (\sin(\delta) / \delta)) \bar{b}}{r\omega^2} \quad (\text{eq. 11}).$$

The scale factor calibration is $SF_C = SF_A / SF_N$, where SF_N is the nominal scale factor.

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